Hard bremsstrahlung from femtosecond laser produced copper plasmas

Paramel P. Rajeev, Sudeep Banerjee, Arvinder S. Sandhu, Riju C. Issac, Lokesh C. Tribedi and G. Ravindra Kumar*

Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India

Abstract

We present measurements of x-rays in the 30-500 keV energy range from 100 fs, 806 nm laser pulse produced copper plasmas at intensities in the range of 10^{15}–10^{16} W cm^{-2}. We show that surface roughness has a major role in enhancing the x-ray yield and hot electron temperature. Roughness appears to remove the differences in the interaction of s-polarized and p-polarized light with the plasma.

PACS :52.25.Nr, 52.40.Nk, 52.50.Jm, 42.65.Re

* E-mail: grk@tifr.res.in. Author for correspondence

The behaviour of matter under extremely intense, ultrashort light pulse irradiation is an exciting area of contemporary research. The development of ultra-high intensity subpicosecond lasers through the process of chirped pulse amplification has opened up new realms in the study of laser matter interaction both above and below the breakdown threshold of a solid[1]. Solid density plasmas with steep density gradients and temperatures of hundreds of kilo electron volts can be produced at the focal spot of an intense, femtosecond laser. Such plasmas are remarkably different from conventional laboratory plasmas. They are formed within a few optical cycles and are `point' (micron sized) sources for soft and hard x-rays[2-4] and gamma rays[5,6]. The potential for creating high brightness x-ray sources has attracted multifaceted research to explore various applications like x-ray lithography and time resolved x-ray diffraction[1]. In addition to the large x-ray yield both in continuum and line emissions, an exciting property of such x-ray pulses[7] is their extremely short temporal duration (subpicosecond) which is ideal for time resolved studies at x-ray wavelengths. To be able to use such x-ray sources, it is essential to simply and correctly characterize their emission as well as find ways to enhance it. Recently, Banerjee et al. have demonstrated a simple way of obtaining absolute yields of such x-ray fluxes and pointed out the role of photon statistics in estimating yields from laser produced plasmas using broad band Si (Li) detectors[8,9.] There is a great deal of interest in methods that could enhance the x-ray yield and the influence of various laser and target conditions has been the subject of many recent studies. The effect of a pre-pulse has been investigated in detail. While significant enhancement in the yields is noticed, the x-ray pulse duration tends to become longer[10,11]. Another approach that has begun to attract attention is the role of modulation/roughness of the surface structure in coupling the input light into the plasma and enhancing x-ray yield. Murnane and coworkers[12] have shown absorption of over 90% input light into the plasma formed on grating targets as well as those coated with metal clusters. More recently, impressive enhancements of x-ray fluxes have been achieved in nanohole alumina targets (soft x-ray region)[13], porous silicon[14] and nickel `velvet' targets (hard x-ray region)[15]. There have, however, been no reported attempts to enhance the yield of x-rays in the very hard region (>10 keV). Such studies should be interesting not only from the point of view of enhancing the x-ray yields, but also to understand the role of surface structuring/modulation in the generation of hot electrons that are responsible for the emission in this region. During the course of our studies of hard and very hard bremsstrahlung emission, we noticed that normal (unpolished) targets gave rise to hot electron temperatures much higher than expected and observed for polished targets. In this paper, we present measurements of the bremsstrahlung emission in the 30-500 keV region for polished and unpolished copper targets and comment on the possible influence of roughness on the polarization dependence of the x-ray emission.

A schematic of the experimental set up is shown in Fig.1. A Ti: Sapphire laser operated at 806 nm, 100 fs was focused with a 30 cm focal length lens at 45 degrees angle of incidence on to copper targets housed in a vacuum chamber at 10^{-3} torr. The femtosecond laser is a custom-built chirped pulse amplification system with two-stage multipass amplification. The maximum pulse energy used in the current experiments is 6 mJ, giving a maximum focussed intensity of about 2×10^{16} W cm^{-2} with a focussed spot size of 20 μm. A thin half wave plate was introduced in the beam path in order to change between S and P polarization states. The target was constantly rotated and translated in order to avoid multiple hits at the same spot by the laser pulses. X-ray emission from the plasma was measured along the plume direction by a 1.5 inch NaI (Tl) detector, which was calibrated using Co^{57} and Cs^{137} sources. The BK-7 window of the vacuum chamber sets the lower energy cutoff for the observed emission. The output of the detector was amplified and then fed to a multichannel analyzer through an ADC. Spectra were typically collected over 30000-40000 laser shots. The x-ray spectra are corrected for the efficiency of the detector-window assembly. In order to reduce the pile up effect the count rate was reduced to less than 0.2 per laser shot by introducing suitable lead apertures in front of the detector. Typical solid angle of observation was in the region of 50-80 μsr. Electronic gating techniques were used to eliminate cosmic ray and other noise and obtain nearly background free signals[16].

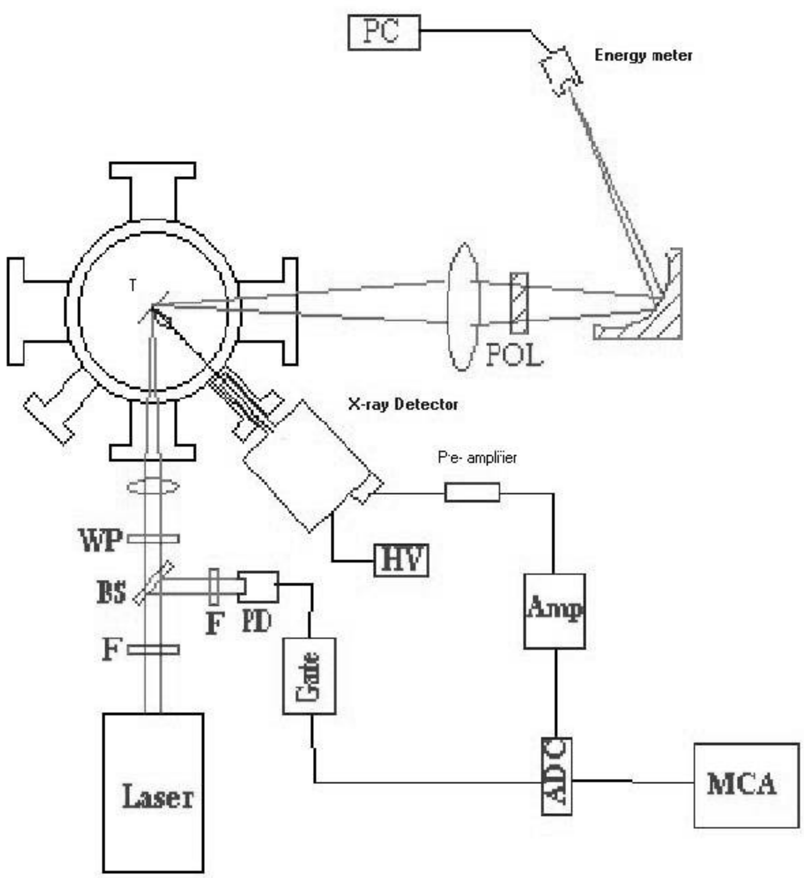

Figure 1- Experimental set-up for x-ray and reflectivity studies (the latter part is not relevant for this paper). F - Thin neutral density filter, BS - Beam splitter, WP - Wave plate, PD - Photo diode, HV - High voltage

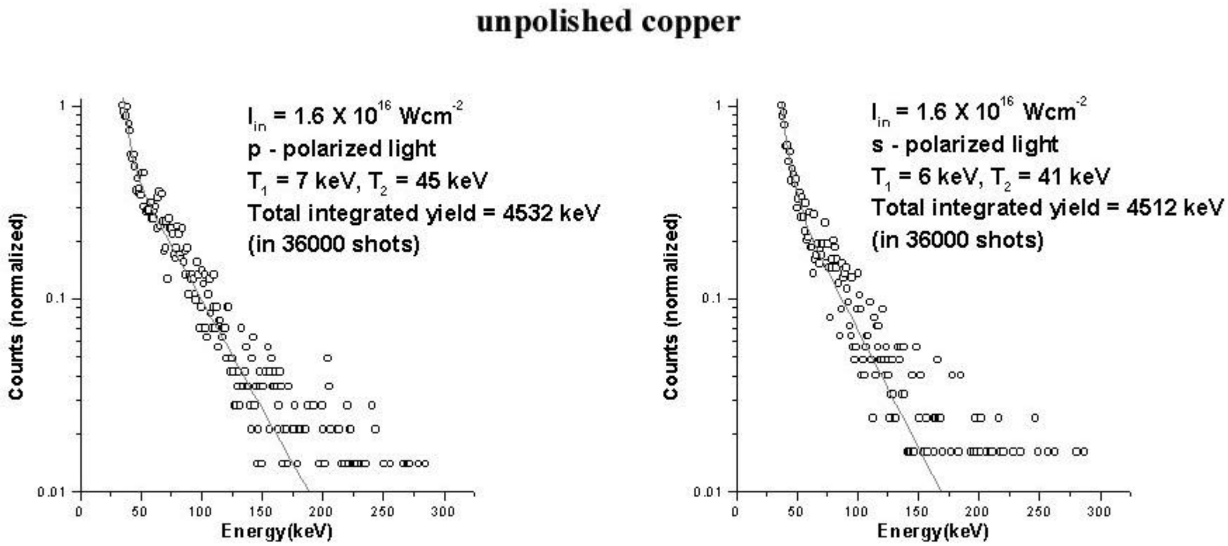

Figure 2 - Bremsstrahlung emission from unpolished copper target

Fig. 2 shows the bremsstrahlung emission measured in the 30-500 keV region for a normal (unpolished) copper target at an intensity of 1.6 x 10^{16} W cm^{-2}, for S and P polarizations of input light. The solid line fits indicate the existence of at least two temperature components for the hot electrons in the plasma. These turn out to be 6 keV and 41 keV for S polarization, while they are 7 keV and 45 keV for P-polarized light. The space and energy integrated yield, under the assumption of isotropic emission, gives an overall efficiency (keV/keV) of about 2 x 10^{-5} for conversion into the 50-300 keV region.

Let us consider the data for p-polarized light first. In this case, it is well known that the hot electrons could be generated by two mechanisms – resonance absorption (RA) and vacuum heating (VH) for our pulse duration and angle of incidence. RA has been well studied both experimentally[17,18] and theoretically[19,20]. Based on the observations and simulations, the following scaling law has been established.[19]

$$T_{hot} = 14\, T_c^{0.33} (I\lambda^2)^{0.33}$$

Where T_c is the background electron temperature in keV, I is the intensity of the laser in units of 10^{16} W cm^{-2}, λ is the wavelength in microns. According to this scaling law, for a T_c of 0.5 keV, we get a T_{hot} of 9.6 keV under our conditions for RA. This temperature is close to the lower component that we have measured in our experiments. RA cannot, however, explain the higher component. VH[21,22] can be examined as a possible candidate for the generation of this component. A crucial requirement for VH is that the electron oscillatory amplitude (x_{osc}) is larger than the plasma scale length (L). Our laser pulses have an insignificant pre-pulse component and the measurements of Doppler shift from plasma expansion has indicated[23] that the ratio x_{osc}/L about 1.0 and L/λ is about 0.1. For these parameters, simulations[24] have indicated that VH could give a T_{hot} of about 40 keV, which is not too far from what we have measured for the higher component. Such an interpretation, however, has to be examined in the light of the data for S-polarization. In this case, there is no known mechanism (operative under our conditions) that can explain the lower hot electron temperature, let alone the higher one. The only mechanism that one can invoke is collisional absorption, which is not very effective above 10^{15} W cm^{-2}. Surprisingly, not only are there hot temperature components in our S polarization data, but their magnitudes are quite comparable to those generated by P polarized light. Further, the x-ray yields are almost equal for both polarizations. Hence, we are forced to reexamine the possible causes of the hot electron generation in our experiments.

One possible cause of hot electrons that we studied was surface roughness (structuring/modulation). It has been pointed out in many studies (see references below) that a number of efficient schemes – surface waves, multiple scattering, trapping of energetic electrons and light etc.- exist for the coupling of laser light into the plasma for rough surfaces. The understanding thus far is that structuring of the surface leads to localized volume heating of micro regions of the target leading to denser plasmas and higher temperatures[13, 15, 25]. To investigate the level of roughness on our surface, we took an AFM image of the targets used in our measurements, a typical one of which is shown in Fig. 3(a). It is obvious that the surface is quite uneven, with the rms peak-valley difference being 0.1 μm. We decided to investigate x-ray emission of a highly polished surface an AFM image of which is shown in Fig.3 (b). This surface has an rms peak-valley separation of 5 nm, which is 20 times smaller than the unpolished target. This polished target is evidently much smoother than the earlier unpolished target we discussed.

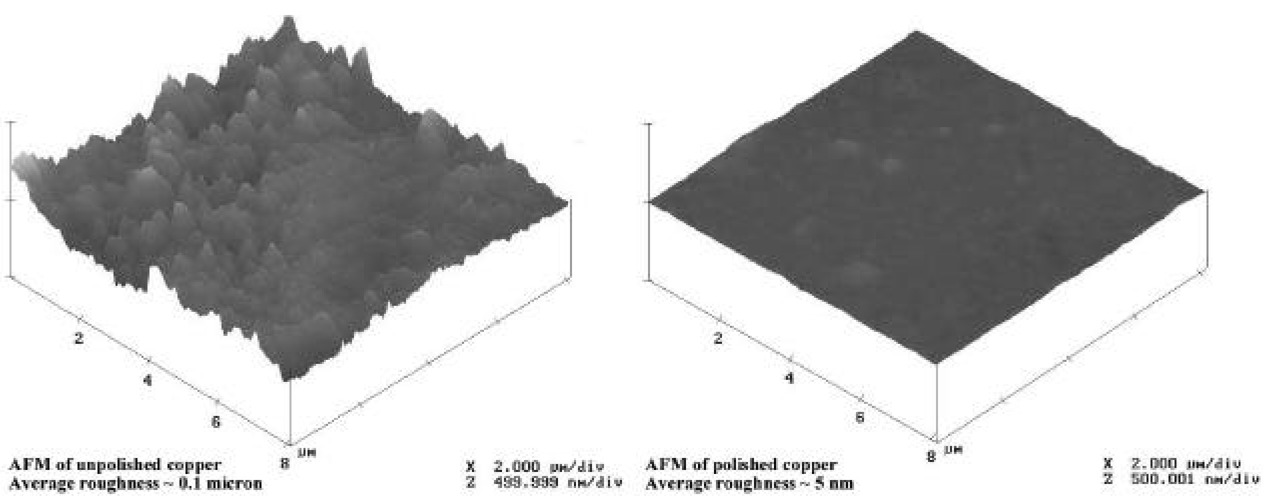

Figure 3 - AFM images of the targets used. Fig. 3 (a) is the image of the unpolised copper and Fig.3 (b) is that of the polished one

Fig. 4 shows the bremsstrahlung data of polished surfaces under conditions similar to those described above for unpolished targets. There are significant differences in these spectra. The yield for P polarization is about 6 times larger than that for S polarization as expected by the large coupling of the former into the plasma by RA and VH. For P polarization there are still two temperatures (2 keV and 28 keV). The lower component is much smaller than (1/3) the value obtained for unpolished targets in this laser energy range. Further, the yield at the high temperature

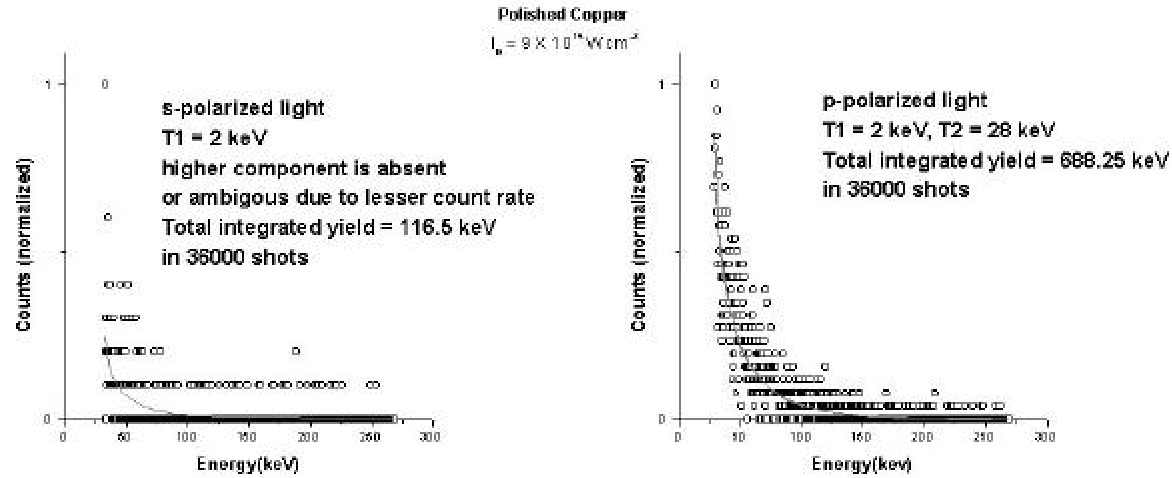

Figure 4 - Bremsstrahlung emission from polished copper target

is much weaker for the polished target. Next, the S polarization has only one unambiguous temperature component. Moreover, the yield (integrated from 30 keV to 500 keV) in this case is found to be substantially lower than the value in the unpolished case. These observations lead us to infer that the roughness on the unpolished target could be responsible for the observed high temperatures and yields of bremsstrahlung. Fig. 5 presents the comparative picture for unpolished and polished targets for p-polarization at the same laser intensity. The differences in the spectra are striking, with the unpolished target showing relatively large emission up to and beyond 200 keV. The temperature decreases by more than a factor of 2 for polished targets. We estimated the ratio of the relative weight of the higher temperature component in the unpolished to that in the polished case for P polarization case to be 10.

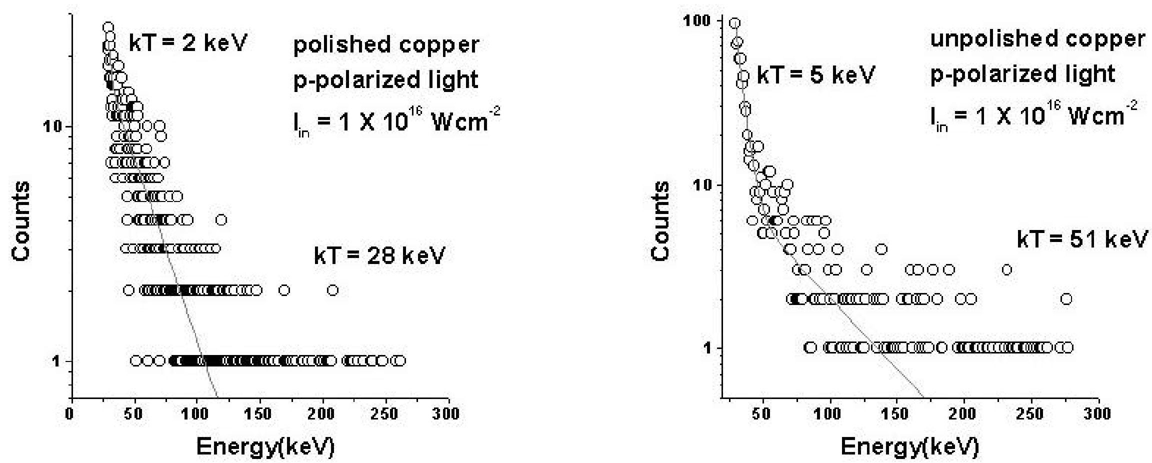

Figure 5 - Comparison of bremsstrahlung emission from polished and unpolished targets under the same conditions

Another interesting feature that emerges is the relative lack of dependence of the emission on the polarization in case of the unpolished target. We could attribute this to many factors – 1. The lack of a definite geometry on the surface because of which polarization could be considered either S or P depending on the local topographical feature at the point of incidence, 2. Modification of polarization by scattering from the rough features and 3. Possible depolarization of the incident light by multiple scattering. All these factors could imply that the influence of roughness could override the role of polarization in light coupling to the plasma. We note that Ahn et al.[26], have seen similar lack of dependence of soft x-ray yield on the light polarization state though they could not identify a reason for such behaviour. They cited rippling of the critical surface as a possible cause. More investigations are needed to study this problem in detail and we are in the process of studying the influence of controlled modification of surface roughness on hard and very hard x-ray emission

Zhang et al.[6] reported temperatures of 18 keV and 83 keV for hot electrons from copper plasmas under intensities and angle of incidence similar to ours – the former without a prepulse and the latter with an 8% prepulse at 70 ps before the main pulse. It is interesting to note that the scaling laws for RA give a temperature of about 9 keV, half the value they measured in the prepulse free case. It leads us to speculate that surface roughness may have played a significant role in their experiment, because their `polished' surface has a finish (<1 μm) that is similar as or inferior to our unpolished targets. Ahn et al. have shown that RA is very effective for large delay between the prepulse and main pulse[26]. In view of this, we point out that prepulse enhancement of x-ray emission might not lead to very high hot electron temperature because an expanding plasma precludes VH from operating[21,24] and RA is not as effective as VH for generating high temperatures[24].

In conclusion, we have demonstrated that the roughness of ordinary, unpolished, readily available surfaces could be used to produce enhanced yields of hot electrons which in turn lead to larger fluxes of ultrashort x-ray pulses in the very hard x-ray region.   A key observation is the lack of influence of the polarization state on the hot electron temperatures and yields in the case of unpolished targets, in stark contrast to the observations for polished, flat targets. Further experiments are under way to study the hot electron generation in targets with tailored roughness.

We thank S.P. Pai for the AFM images and P.K.Kaw and Sudip Sengupta for discussions. The high energy, femtosecond laser facility has been funded by the Department of Science and Technology, New Delhi.

---

1. P. Gibbon, and E. Forster, Plasma Phys. & Control. Fusion **38**, 769 (1996)
2. J. C. Kieffer, M. Chaker, C. Y. Cote, Y. Beaudoin, H. Pepin, C. Y. Chien, S. Coe, and G. Mourou, Appl. Optics **32**, 4247 (1993)
3. H. Chen, B. Soom, B. Yaakobi, S. Uchida, and D. D. Meyerhofer, Phys. Rev. Lett. **70**, 3431 (1993)
4. D. Giulietti, and L. A. Gizzi, La Rivista del Nuovo Cimento **21**, 1 (1998)
5. J. D. Kmetec, IEEE J. Quant. Electr. **28**, 2382(1992)

6. P. Zhang, J. T. He, D. B. Chen, Z. H. Li, Y. Zhang, J. G. Bian, M. Wang, Z. L. Li, B. H. Feng, X. L. Zhang, D. X. Zhang, X. W. Tang, and I. Zhang, Phys. Rev. E **57,** R3746 (1998)
7. M. Murnane, H. Kapteyn, M. D. Rosen, and R. Falcone, Science **251**, 531(1991)
8. S. Banerjee, G. R. Kumar, A. K. Saha, and L. C. Tribedi, Optics Communications **158**, 72 (1998); Phys. Scr. **T80**, 539 (1999); S. Banerjee, G. R. Kumar, and L. C. Tribedi in K. K. Sud, and U. N. Upadhyaya (Eds) *Trends in Atomic and Molecular Physics* (Kluwer, 2000), p1.
9. S. Banerjee, G. R. Kumar, and L. C. Tribedi, Eur. Phys. J. D **11**, 295 (2000)
10. J.F. Pelletier, M. Chaker and J.-C. Kieffer, J. Appl. Phys. **81,** 5980 (1997)
11. H. Nakano, T. Nishikawa, H. Ahn, and N. Uesugi, Appl. Phys. Lett. **69**, 2992(1996)
12. M. M. Murnane, H. C. Kapteyn, S. P. Gordon, J. Bokor, E. N. Glytsis, and R. W. Falcone, Appl. Phys. Lett. **62**, 1068(1993)
13. Tadashi Nishikawa, Hidetoshi Nakano, Naoshi Uesugi, Masashi Nakao, and Hideki Masuda, Appl. Phys. Lett. **75**, 4079(1999)
14. Tadashi Nishikawa, Hidetoshi Nakano, Hyeyoung Ahn, and Naoshi Uesugi, Appl. Phys. Lett. **70**, 1653(1997)
15. G. Kulcsar, D. AlMawlawi, F. W. Budnik, P.R. Herman, M. Moskovits, L. Zhao, and R. S. Marjoribanks, Phys. Rev. Lett. **84**, 5149(2000)
16. S. Banerjee et al.(*in preparation*)
17. M. Schnurer, R. Nolte, T. Schlegel, M. P. Kalachnikov, P. V. Nickels, P. Ambrosi, and W. Sandner, J. Phys. B: At. Mol. Opt. Phys. **30**, 4653(1997)
18. S. Bastiani, P. Audebert, J. P. Geindre, T. Schlegel, J. C. Gauthier, C. Quoix, G. Hamoniaux, G. Grillon, and A. Antonetti, Phys. Rev. E **60**, 3439(1999)
19. D. W. Forslund, J. M. Kindel, and K. Lee, Phys. Rev. Lett. 39, 284(1977)
20. K. Estabrook and W. L. Kruer, Phys. Rev. Lett. **40**, 42 (1978)
21. F. Brunel, Phys. Rev. lett. **59**, 52 (1987)
22. M. K. Grimes, A. R. Rundquist, Y. S. Lee, and M. C. Downer, Phys. Rev. Lett. **82**, 4010 (1999)
23. A. S. Sandhu(*private communication*)
24. Paul Gibbon, and A. R. Bell, Phys. Rev. Lett. **68**, 1535 (1992)
25. C. Wulker, W. Theobald, D. R. Gnass, F. P. Schafer, J. S. Bakos, R. Sauerbrey, S. P. Gordon, and R. W. Falcone, Appl. Phys. Lett. **68**, 1338 (1996)
26. H. Ahn, H. Nakano, T. Nishikawa, and N. Uesugi, Jpn. J. Appl. Phys, (Pt.2 Lett). **35**, L154 (1996)